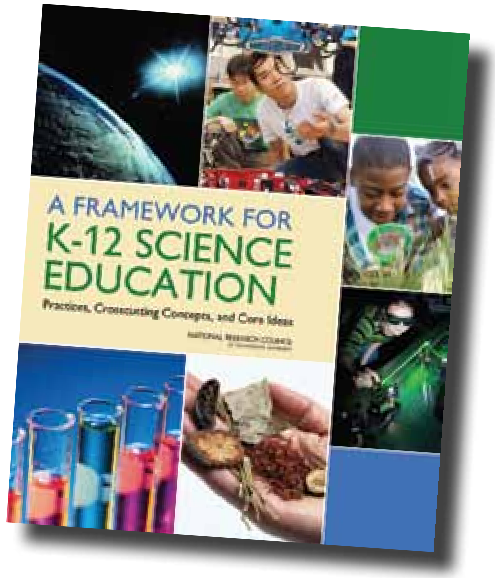
Engaging Students in the Scientific Practices of Explanation and Argumentation

Understanding *A Framework for K–12 Science Education*



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A Framework for K–12 Science Education identifies eight science and engineering practices for K–12 classrooms. These practices, along with core ideas and crosscutting concepts, define our nation's learning goals for science. An important advance from earlier standards (AAAS 1993, NRC 1996), these practices are clearly identified *not* as separate learning goals that define what students should know *about* the process of science. Instead, the scientific practices identify the reasoning behind, discourse about, and application of the core ideas in science.

The practices outlined in the framework are:

- Asking questions and defining problems
- Developing and using models
- Planning and carrying out investigations
- Analyzing and interpreting data
- Using mathematics and computational thinking
- Constructing explanations and designing solutions
- Engaging in argument from evidence
- Obtaining, evaluating, and communicating information

In this article, we examine the sixth and seventh practices concerning explanation and argumentation, respectively. The two practices depend on each other: For students to practice explanation construction, they must also engage in argumentation.

The *Framework* elaborates on how inquiry was expressed in prior standards to add an emphasis on the sensemaking aspects of science (Bybee 2011). The notion of practices moves from viewing science as a set of processes to emphasizing, also, the social interaction and discourse that accompany the building of scientific knowledge in classrooms. This move toward scientific practice requires that we consider the role of argumentation in building knowledge in science because thoughtful and reflective efforts to design investigations, develop models, and construct explanations require critically comparing alternatives, evaluating them, and reaching consensus. In this article, we first define argumentation and explanation individually and then explore their relationship in classroom examples.

Constructing Explanations

The question "Can you explain that?" is answered in various ways in classrooms. Classroom communities may "explain" by clarifying one's meaning (providing definition), identifying a causal mechanism (explaining why something occurred), or justifying an idea (explaining why one believes the idea) (Braaten and Windschitl 2011). The *Framework* defines explanations as "accounts that link scientific theory with scientific observations or phenomena" (Chapter 3), emphasizing that a central form of explanation in science (aaclassroom or professional) is a causal explanation that identifies the underlying chain of cause and effect. This sort of explanation can be evaluated based on whether it can coherently account for—or explain—all of the data students have gathered (Chapter 3).

The scientific practice of explanation goes beyond defining or describing a named process and links a chain of reasoning to the phenomenon to be explained. So rather than asking students simply to explain cellular respiration, we might ask them to explain *why* a person's exhaled air contains less oxygen than the inhaled air. The explanation should not only describe respiration but also

produce a causal chain that fits the evidence that leads to a claim about why oxygen is needed. Such a chain might specify where glucose goes within the body and what materials can enter and exit cells and conclude that a chemical reaction requiring both glucose and oxygen must take place in cells to convert energy to a usable form (Chapter 9).

In articulating goals for explanation, the *Framework* highlights the process of evaluating ideas to reach the best explanation, including that students should be able to:

- Use primary or secondary scientific evidence and models to support or refute an explanatory account of a phenomenon.
- Identify gaps or weaknesses in explanatory accounts (their own or those of others).

Thus, developing explanatory accounts includes not only construction but also comparison and critique. Attempts to construct new explanations typically require elements of argumentation to support and challenge potential explanations. Indeed, effective classroom supports for scaffolding explanations reflect these elements of argumentation, such as prompting students to support claims with evidence and reasoning (McNeill and Krajcik 2012; Sutherland et al. 2006). We turn next to unpacking this aspect of scientific practice.

Engaging in argument from evidence

The practice of arguing from evidence foregrounds the understanding that scientific knowledge is built through "a process of reasoning that requires a scientist to make a justified claim about the world. In response, other scientists attempt to identify the claim's weaknesses and limitations" (NRC 2011). This process of scientific argumentation occurs when a claim, perhaps a proposed explanation, is in doubt or is contested (Osborne and Patterson 2011), thereby motivating participants to defend their own and challenge or question alternatives (Berland and Reiser 2009). Chapter 3 of the *Framework* (NRC 2011) teases apart several goals that refer to supporting and contesting knowledge claims:

- Construct a scientific argument showing how the data support the claim.
- Identify possible weaknesses in scientific arguments, appropriate to the students' level of knowledge, and discuss them using reasoning and evidence.
- Identify flaws in their own arguments and modify and improve them in response to criticism.

Scientific knowledge building combines these practices, constructing candidate explanations of natural phenomena and arguing for those claims. As scientists consider alternative interpretations of the same observations, they argue to identify weaknesses in various explanations and incrementally construct a consensus account (possibly drawing elements from multiple sources), arriving at the explanation that best fits the evidence. This interdependence is an example of how the practices interrelate: In response to questions, explanations are developed through analyses of data from investigations and refined through argumentation.

What makes these practices?

The *Framework* uses "the term 'practices,' instead of a term such as 'skills,' to stress that engaging in scientific inquiry requires coordination both of knowledge and skill simultaneously" (NRC 2011, Chapter 3). Bybee (2011) emphasizes this expansion of inquiry into the notion of practices to learn "about experiments, data and evidence, social discourse, models and tools," and to engage in using these to "evaluate knowledge claims, conduct empirical investigations, and develop explanations." The practices involve *doing* the work of building knowledge in science and *understanding* why we build, test, evaluate, and refine knowledge as we do. This involves students engaging and reflecting on the practices to develop a sense of *how* the scientific community builds knowledge. This is made explicit in the additional goals that specify that students should be able to explain how and why they engage in argumentation:

- Recognize that the major features of scientific arguments are claims, data, and reasons and distinguish these elements in examples.
- Explain the nature of the controversy in the development of a given scientific idea, describe the debate that surrounded its inception, and indicate why one particular theory succeeded.
- Explain how claims to knowledge are judged by the scientific community today and articulate the merits and limitations of peer review and the need for independent replication of critical investigations.

Developing these understandings of scientific knowledge building requires adopting the goals of these practices. If we expect students to learn that the scientific community builds knowledge by constructing explanations and arguments, then they must experience using these practices to address questions they have identified. Furthermore, the student participation must be *meaningful*, so that students argue to resolve inconsistencies in their explanations and not because their teacher asked them to (Berland and Reiser 2009).

We illustrate this idea of meaningful engagement in

explanation and argumentation through four classroom examples.

Example 1—Arguing for Predictions Strengthens Explanations

In the first example (Hammer and van Zee 2006), we see that students encouraged to defend their predictions constructed causal explanations about why differently shaped objects fall to the ground at different rates (Core Ideas PS2.A and PS2.B). On the first day of this investigation, first-grade students and their teacher worked to explain what happened when they dropped a sheet of a paper and a book. They concluded that the book falls first because it has "more strength" (the students' word for weight). This discussion also introduced ideas related to gravity and wind resistance. On the second day, the class predicted what would happen if they dropped a book and a crumbled piece of paper. Brianna predicted that "They will fall at the same time 'cause they both got the same strength together." This idea aligned with other student suggestions that the crumpled paper "weighed more" than the original paper. When the teacher questioned how the weight could have changed, Rachel added to Brianna's idea, saying, "The paper… used to be, um, really light… but [now] it probably has as much strength as the book since all the, um, paper is crumpled up together."

After a pause, Brianna said, "If it's balled up, it's still not heavy, it's the same size." Then Brianna questioned her own explanation and pushed the class to reconsider their assumption that the paper weighed more when crumpled. Numerous students said they agree that crumpling paper wouldn't change its weight. Diamond then said: "The first time, like this [flat], and then it balled up." In other words, the paper changed shape. Diamond added that the crumpled paper did not drift to the ground as the flat sheet did. As Brianna stated: "It just drops, kind of like the book." While there is still important work to be done to tease apart shape and weight in the discussion, the example demonstrates how defending (or arguing for) predictions by explaining why the event occurred enabled students to investigate and question their initial assumptions about the paper and the relationship between the paper's shape and its fall to the ground.

Example 2—Reconciling Competing Explanations

In the second example, students develop explanations to defend predictions, as in Example 1, but also reconcile their differences, helping them move toward a more scientifically accurate understanding. In this case, a mixed-grade classroom of fifth-and sixth-grade students investigated how tectonic plates move and interact (Core Idea ESS2.B, 6-8). Before this investigation, students discussed convection currents and constructed models of particular plate boundaries: A third of the class modeled convergent boundaries, a third focused on divergent boundaries, and a third on transform boundaries. On the third day, students formed groups aligned with the three types of boundaries to explore a question that emerged: With all this plate motion, is the Earth staying the same size or getting bigger or smaller?

In one group of four students, two believed the Earth was staying the same size and two thought it was getting bigger. Pint argued that dinosaur fossils "prove" that the Earth is getting bigger because they are evidence that the Earth's layers are getting thicker.

Pint*: You have to dig and dig [to find the dinosaur bones]. So that means the Earth has been getting larger because you have to dig so much to get to bones... (1)

Olive: Yeah, we saw *Jurassic Park*, I guess. (2)

Intervening additional discussion of dinosaur fossils and teacher interruption

Fern: I understand how you think of the dinosaur bones. But those are convergent that have covered the dinosaur bones. But not all convergence makes mountains. Some meet [gestures that plates meet and stay flat]. So the dinosaur bone was one plate and then that plate kind of moved and then that converged and overlapped. (18)

Intervening discussion of whether convergent boundaries always create mountains

Fern: So let's say some dirt moved over here, but then there's some dirt not over there. There still might be dirt over there. So it's still even because that dirt over here came from over there. So the world is even, and it's not growing, because the magma might come in but then it diverges and collapses. (24)

*Students selected their own pseudonyms

This episode illustrates the relationship between argumentation and explanation when students engage meaningfully in the practices. This happens when students actively listen and respond to one another. For example, in line 2 Olive connects her own experiences with Pint's points. Fern, in line 18, similarly addresses her

teammates' ideas about the explanation they are building: "I understand how you think of the dinosaur bones…" (Line 18). Fern then uses the language and imagery of Pint's understanding—that of dinosaur bones proving that the Earth's plates are layering on top of one another—to move the conversation toward her own (more scientifically accurate) understanding, that the Earth "is still even" (the same size). Fern states: "Let's say some dirt moved over here but then there's some dirt not over there…so it's still even because that dirt over here came from over there" (Line 24).

The spontaneity of the students' discourse—they are not looking at a worksheet or obviously thinking about their teacher's expectations—suggests that these interactions are meaningful. The students are actively engaged in figuring this out—in constructing an explanation regarding whether and how the plate motion affects the shape and size of the Earth. A less meaningful engagement is easy to imagine—the students could have been given a worksheet that asked for evidence: "This says we need to find evidence for our idea." Alternatively, they could all have worked to answer the question individually without much cross-talk or requested that their teacher tell them the answer to the question. Instead, however, they are engaged in what appears to be purposeful knowledge-construction interactions.

This interaction provides evidence of both explanatory and argumentative practices. Students work to construct an explanation of how tectonic plate movement affects the shape and size of the Earth. For example, in line 24 Fern offers an explanation regarding *how* the tectonic plates could move without changing the overall size of the Earth. Together students reason how this could occur and also explain Pint's observation that dinosaur bones are "buried." The argumentative nature of the discussion is apparent when they engage in nascent forms of the first two argumentative goals in the *Framework,* justifying their own ideas (lines 1 and 24) and challenging alternative ideas (as Fern challenges Pint).

Example 3—Building consensus from multiple contributions

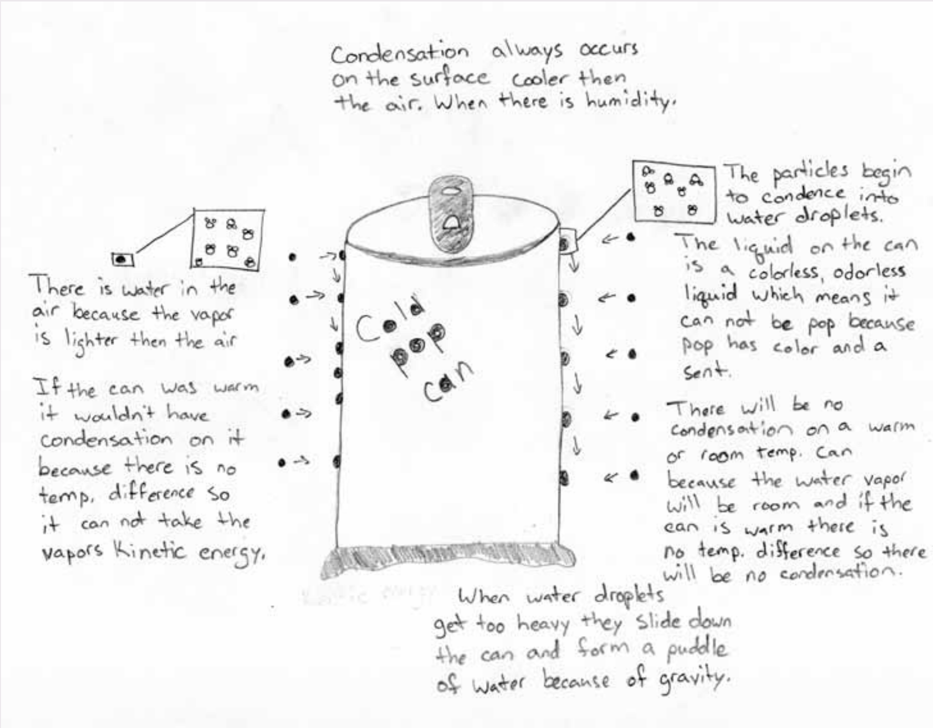
In this third example, fifth-grade students use their ideas to defend, make sense, and build a consensus. The students investigated condensation (Kenyon, Schwarz, and Hug 2008) and represented their explanations for how water appeared on a cold pop can in a diagrammatic model focusing on changes of state. The goal of the unit was an initial form of the particle model (Core Idea PS1.A 3-5), in which the existence of water as particles in gas state can explain where the water comes from in condensation and where it goes in evaporation. The day before this discussion, students in the group evaluated each other's individual models. Here they construct a group consensus model of condensation using ideas from those individual models. (In this classroom, the teacher extended the targeted PS.1.A 3-5 learning goal to also bring in kinetic energy, Core Idea PS3.A 6-8, as part of the explanation).

Amy: Wait guys! Why do we think why condensation shows up? Can anybody? (1)
Amy: Yeah, but why do you think it got there? Because of the water in the air? (2)
Jenny: Because, of the temperature… (3)
Amy: The coldness is taking the kinetic energy from the air…. (4)
Ivan: Coldness isn't a word! (5)
Amy: Okay, does everyone agree that the kinetic energy is taking away from air and turning it into a liquid? (6)
Ivan: Sure! (7)
Amy: We should write when gas loses kinetic energy (KE), it turns into a liquid, and when liquid loses kinetic energy it turns into a solid. Or we could write gases minus KE of the liquid. Liquid minus KE equals… (8)
Ivan: So what are we doing? (9)
Amy: Explanations! (10)
Mary: Condensation always occurs on the surface that is cooler than the air. (11)
Jenny: Okay! (12)
Ivan: Condensation works when the water vapor loses its KE and turns into a liquid. (13)
Amy/Jenny: That's what we said! (14)
Ivan: I know! (15)
Matthew: We can't say condensation ALWAYS OCCURS! (16)
Lori: …always occurs on COLD surfaces! (17)
Matthew: What if you're in a spot that has no humidity whatsoever? (18)
Jenny: Mr. Smith explained that with the warm can in front of the humidifier, nothing happens. (19)
Matthew: Okay. (20)

The conversation, by attempting to fill gaps, involves several important reformulations that clarify the overall explanation. "Water in the air," "temperature," and, later, "kinetic energy" emerge as important steps in the mechanism. Three attempts to formulate what they have figured out (lines 8, 11, 13) lead to Ivan's summary that references water vapor losing kinetic energy and turning to a liquid. Matthew raises a final concern (lines 16, 18) to clarify the conditions under which condensation occurs. In response, important additional qualifications are added by Lori (line 17, the surface must be colder than air) and Jenny (line 19, there must be sufficient water in the air). Consequently,

Figure 1.

A group's articulated model of condensation on a soda can.



Matthew's concern is met by modifying Ivan's proposed explanation to produce a new synthesis, which is reflected in the group's articulated model (See Figure 1).

Example 4—Critique leads to clarified explanation

The final example demonstrates how critiques can lead students to improve and clarify their explanations. In this case, a group of eighth graders undertook an investigation of population change (Core Idea LS4.B). Students shared ideas to account for changes in populations of Galápagos finches over time. Students discovered that during a drought, most of the birds died, and they attempted to explain why the birds died and why others survived (Tabak and Reiser 2008).

Mr. N: So, I get where Ina is going. Can someone put this in other words? What do you mean "the populations adapt"? Ina, you have the floor so you can call, or you can keep pushing on this if you want. (1)

[Ina calls on Joe] (2)

Joe: Well, like the beak length thing. The reason why there were so many birds that had bigger beak lengths in '77 and '78 was well, the ones with the bigger beaks survived, and they mated, so their babies, they had the trait, the bigger beaks. And that's why most of their babies and the adults had bigger beaks rather than medium or small beaks because that trait helped them survive in the drought. [Joe calls on Jeff] (3)

Jeff: The reason the population adapts is to survive. If they don't adapt then they will die so they'll disappear, so yeah... Kelly? (4)

Kelly: Umm, I think it's because the birds with the smaller beaks died, and the longer beaks were able to have children, and their children had longer beaks, so they survived and the trait was being passed on a lot. Ina? (5)

Ina: Umm, I don't think so. Because we have this graph that shows the wet [season] of 1973 to the dry [season] of 1978, and it jumped up. It wasn't that the ones with the shorter beaks died. Even the longest beak here is like pretty much even with the middle of the pack in 1978. Mr. N? (6)

Mr N: So you're saying it's not always every short one dies? (7)

Ina: Yeah. (8)

Mr. N: Okay. Is that true for the moths too? Was it always every peppered moth dies? [The students had earlier explained why some variations of peppered moths survived pollution during the late 1800s.]

Most students: No. (9)

Mr. N: Just, even for the moths, it's kind of like the odds change some, right? (10)

Most students: Yeah. (11)

Teacher: Okay, so I think I get what you're arguing. (12)

This episode shares important aspects with the previous episodes. Like example 2, there are explanatory accounts proposed and a critique raised. A resolution is proposed (in this case by the teacher bringing in features of a prior explanation). This keeps the core of the proposed explanation while addressing the critique (adding that the advantage of a trait is like "odds changing" rather than "always every" bird or moth lacking the trait dies.

Although this excerpt does not go as far toward having the students articulate the consensus that resolves the critique, the class agrees with the teachers' proposed change that handles Ina's concern (line 6), while managing to retain the central parts of the causal chain proposed by Joe (line 3) and Kelly (line 5). In this short excerpt, the students developed a logical chain that reflects some of the most important steps in natural selection: preexisting variation of a trait (beak length), changing environmental conditions ("the drought"), differential survival ("the ones with the shorter beaks died"), and heritability of the trait ("passed on a lot"). (Missing from the account is an explanation for why birds with longer beaks were more likely to survive.)

Conclusions

Across the four examples, we see that students arguing for their explanations can strengthen those explanations and help construct a consensus explanation. We see this in examples 1 and 3, in which the support, defense, and consensus building helped make the explanations more elaborate and precise; and in examples 2 and 4, in which this argumentation made the explanations better able to handle possible contradictions. In this way, the explanations improve along several of the dimensions outlined in the *Framework,* improving the causal account (filling gaps) and articulating and improving their fit with evidence.

In addition, in each of these examples the students engaged in meaningful forms of scientific practices—they were working to make sense of scientific phenomena rather than working to replicate the understandings communicated by a textbook or other authority. These examples illustrate student engagement in the practices of science rather than in the processes or skills of science. Together, these examples illustrate the importance of considering how the scientific practice of argumentation plays a role in bringing explanations into K–12 classrooms.

These examples and related research suggest how classroom environments might support this meaningful engagement in scientific practice. We, as educators, must create situations that enable students to interpret the practices of explanation and argumentation as something they could reasonably do to construct knowledge (Berland and Hammer 2012). This requires focusing on reasons for ideas, rather than only on the accuracy of a particular idea (Sutherland et al. 2006). It requires creating a climate that is safe for students to be wrong as they work toward more complete explanations. It also requires asking students rich questions that have multiple plausible answers so that students can discuss and reconcile them, developing consensus explanations. ■

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